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# Economic evaluation of decentralized pyrolysis for the production of bio-oil as an energy carrier for improved logistics towards a large centralized gasification plant

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ABSTRACT

In the present study, the potential of biomass-to-bio-oil conversion as an intermediate process step to increase product energy density and subsequently decrease transport-related costs is examined. The scheme under investigation consists of two steps; (1) decentralized bio-oil production from biomass gathered from a certain area and (2) transportation of the produced bio-oil to a central destination (bio-refinery, power plant, etc.). The supply chain is compared to one based on direct solid biomass transportation from the circular source to the central plant. The best case scenario of the biomass-to-bio-oil conversion scheme involves an 80 dry t/h fast pyrolysis unit and utilization of the by-product char for electricity production, while the bio-oil is transported by pipeline. For central transportation distances ranging from 100 to 500 km, the centralized unit yard cost of woodchips-derived bio-oil is equal to 0.030–0.035 €/kWh$_{th}$, while the respective cost for directly transported biomass varies between 0.015 and 0.024 €/kWh$_{th}$. It can therefore be concluded that the capital and operating costs of fast pyrolysis units are still high, hindering any benefits from cost-effective transportation of the bio oil.


**Contents**



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## 1. Introduction

The upgrade of low energy density solid biomass to liquid bio-oil from 0.1 to 0.8 t/m$^3$ [1,2] to 1.2 t/m$^3$ [1–4] and from 1.5–14.8 GJ/m$^3$ [1,2,4] to 20.4–26 GJ/m$^3$ [1,2,5–7] through the fast pyrolysis process has become extensively investigated. The use of biomass as a fuel for bio-refineries and power plants is associated with high transportation costs, mainly due to its relatively low energy density [2,8,9], which is approximately 1/8th of that of coal [9]. Kumar et al. [10,11] have shown that the cost of biomass transportation in a biomass-to-ethanol conversion scenario is between 25% and 50% of the total production cost. For the production of electricity, transport costs can reach values from 25 to 45% of the total electricity production cost [9].

A much discussed way to overcome this issue is the decentralized conversion of the locally produced solid biomass to bio-oil, a liquid product of much higher energy density (up to 7 times [2]) and better fuel quality, through the fast pyrolysis process [1,2,12,13]. Apart from its higher bulk density, ranging between 8 and 12 times that of biomass, bio-oil exhibits some additional advantages such as better handling and storing efficiency at a lower cost [2,14]. In [2] it is shown that the land requirements of a bio-oil handling facility are significantly lower than those of a woodchip handling system (1.8 in contrast to 3.9 ha for a 50 MW$_e$ plant), with a subsequent impact on the land costs. Furthermore, it is shown that bio-oil handling systems have less moving equipment and labor associated with them, resulting in lower operation and maintenance costs.

In addition to this, bio-oil is considered an appealing feedstock for biorefineries owing to its high versatility, since it presents a potential for a wide range of uses. Certain utilization pathways encompass the upgrade and refining of the fuel through technologies such as gasification and synthesis, fluid catalytic cracking, hydroprocessing, and steam reforming. The possible final products include biofuels (biohydrogen, bioethanol, transportation fuels, etc), chemicals and other materials [5,14–17]. Other options are the heat and power production [15,18,19]. It should be noted that although bio-oil has been tested as a fuel for electricity production in properly modified gas turbines and diesel engines [20], it still cannot be used as a transportation fuel in its present form [7]. This is mainly due to its high acidity, low thermal stability and calorific value, high viscosity and poor lubrication compared to light and heavy fuel oils [7,20,21]. Other disadvantages include the higher content of solid particles and ash present in bio-oil mixtures, which is detrimental to the efficiency of combustion processes [21]. A possibly viable method to ameliorate the problematic properties of bio-oil investigated by Ikura et al. [22] regards its mixing with No. 2 diesel fuel. On the other hand, certain studies have shown that bio-oil could replace light and heavy fuel oils in industrial boiler applications [18,23].

The purpose of the present study is to estimate the production cost of fast pyrolysis bio-oil for different biomass species and reactor capacities and to investigate the potential of the decentralized fast pyrolysis process to reduce the increased costs related to biomass transportation to central plants. The parameters taken into consideration are the biomass annual feed to the pyrolysis plant, its purchase price, surface density, chemical composition and energy content.

The biomass-to-bio-oil conversion and transportation scenario is compared to a scenario involving direct biomass transportation. For the more accurate calculation of fast pyrolysis product yields, composition and energy content with respect to the biomass

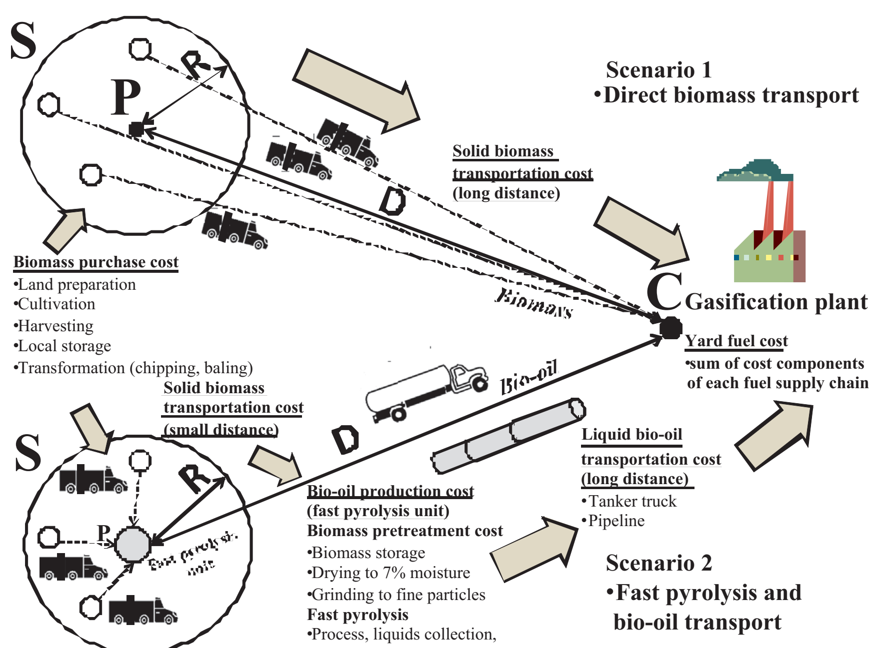



**Fig. 1.** Overview of biomass-to-bio-oil conversion though fast pyrolysis as a concept to reduce fuel transportation costs from a biomass source area to a central gasification plant. The cost components of each fuel supply scenario are also included.

species considered, a model is implemented. The two supply chains and their cost constituents, which will be extensively discussed in the following sections, are depicted in Fig. 1. Before the steps of the methodology that will be followed are presented (Section 3), an overview of the fast pyrolysis process, bio-oil fuel and the technology status follows.

## 2. Overview of the fast pyrolysis process for bio-oil production

### 2.1. The fast pyrolysis process

Pyrolysis, the thermal decomposition of the organic structures (cellulose, semi-cellulose and lignin) of biomass occurs when the latter is heated in the absence of an oxidizing medium [15,24]. The resulting products are of solid (char), liquid (bio-oil) and gaseous (permanent gases) phase [24]. While the main product of slow and mild pyrolysis processes (i.e. torrefaction) is solid [25] fast pyrolysis has been presently optimized for maximizing the yield of bio-oil. Therefore, the process temperature is strictly controlled to about 500 °C [1,12–14,26] the heating rate is extremely high ($10^3$ °C/s to $10^5$ °C/s [23,26] or reportedly 50 W/cm$^2$ [23]), while the vapor residence time in the reactor is kept very short (0.5–2 s) [5,12,26]. Higher and lower reaction temperatures have been associated with increased gas and solid yields respectively [5,27,28]. The produced char is immediately separated from the pyrolytic volatiles though cyclones in order to suspend its catalytic behavior over secondary cracking reactions [5,24,29] and the volatiles are rapidly quenched. A fraction of them (water and organic tars) condenses and forms bio-oil, while another (composed mainly of the gases CO, $CO_2$, CO, $H_2$ and light hydrocarbons) remains in gaseous phase in ambient conditions [29]. Provided the aforementioned conditions of fast pyrolysis are met, the yield of bio-oil can reach values between 70 and 80% (depending on the feedstock [15]) while the yields of char and permanent gases are at about 12 and 13% of the dry feed, respectively [5,19]. For comparison, slow pyrolysis processes produce ~30% liquid, ~35% gases and ~35% char [23]. It should be pointed out that apart from the reaction conditions, the ash contained in the original biomass is one of the most influential parameters in the process [15]. It has been observed that high ash contents lead to an increased formation of water, gases and char while diminishing the yield of the organic liquids [6,15,20,30,31]. This effect has been attributed to the catalytic role of alkaline metals (mainly potassium and phosphorus [15,32,33] ) over secondary reactions in the pyrolytic liquids [6,31,34]. A proposed way to avoid the detrimental effect of the ash content on the bio-oil yield and quality is washing the feedstock with water or acid prior to pyrolysis [31,35].

### 2.2. Bio-oil properties overview

Bio-oil can be considered as a mixture of water (10–30%) and of a great number of organic molecules (70–90%) [5,7,20]. These molecules include species such as acids, alcohols, ketones, aldehydes, phenols, ethers, esters, sugars, furans, nitrogen and other multifunctional compounds [26,36], the majority of which have not been identified [37].

For the time being, the number of organic compounds identified in different bio-oils exceeds 300 [26]. Because of its high water and oxygen content, bio-oil is polar and immiscible with non-polar hydrocarbon fuels [4]. As reported in [38], although bio-oil is miscible with polar solvents such as methanol and acetone, it is immiscible with petroleum derived fuels.

The elemental composition of bio-oil is very similar to that of the original biomass [7]. Its density is roughly 1.2 t/m$^3$ while its high heating value ranges between 15 and 20 MJ/kg (wet basis) depending on its water content [5,26,39,40], being approximately equal to 42% of the heating value of light fuel oil [38]. Its viscosity ranges between 25 and 1000 m$^2$ s$^{-1}$ [38]. Due to its higher energy density, bio-oil can be transported at a much lower cost than biomass, while at the same time being more effectively handled, with substantially lower storage requirements. Moreover, the gasification of bio-oil is another aspect offering many advantages compared to biomass, since the fuel's homogeneity and significantly lower ash content make it possible to diminish downstream syngas requirements [41].

### 2.3. Geographical prospective of bio-oil production

The scope of this study does not focus on a specific geographic region and aims to have a rather generic character. However, the majority of the techno-economic investigations on bio-oil production from fast pyrolysis found in the literature is, to the knowledge of the authors, rather limited geographically to the EU countries, the USA and Canada (indicative references: [6,12,16,37,39,42–44]). In addition to this, most of the up scaling efforts of the fast pyrolysis process, involving the development of units that are reaching demonstration and commercial level, are situated in the USA (with organizations and companies such as Ensyn, GTI, KiOR, Red arrow, RTI International), Canada (ABRITech/Advanced Biorefinery Inc, Forespect, Agri-Therm/University of Western Ontario, Ensyn, Dynamotive, RTI, Pyrovac), Northern and Central Europe countries such as the Netherlands (BTG, Empyro), Finland (Metso, VTT) and Germany (KIT/Lurgi, Fraunhofer, Pytec) [5,15,40]. The intense research and industrial activity on the fast pyrolysis technology in the above regions can be attributed to the large quantities of biomass available in North America and North and Central Europe, in conjunction with the environmental policies adopted by these countries to decrease $CO_2$ emissions and the subsequent increase of interest in the production of biofuels. As a matter of fact, in the USA, fast pyrolysis has recently become recognized as a key route for liquid biofuels production, as it is illustrated from the Department of Energy (DOE) funding strategy [45].

On the other hand, in Southern Europe, although there is a large biomass potential, factors such as absence of established biomass market and high transportation costs in case of forestry biomass do not encourage the biofuels commercialization [46]. This fact is mirrored on the pyrolysis plants development, the extent of which is quite restricted in this region, in comparison to the northern Europe.

According to relevant review studies on the bioenergy situation in Greece, the utilization of biomass sources such as wood pellets [47], agricultural residues [48] and energy crops [49] for biofuels production has promising prospects, in general terms. As far as the technology of pyrolysis conversion is concerned, a demonstration slow pyrolysis plant operated in Evritania region of Central Greece with 1200–1450 kg/h capacity of forestry biomass [50]. The importance of technical improvements required at the time (1995) for the separation of the produced char from the volatiles was emphasized. The authors also concluded that pyrolysis is a promising method for the valorization of forestry residues and agricultural waste of little value and for minimizing the potential for forest fires. However it was underlined that before the technology can be fully implemented in the country, concerns pertaining to the adequacy of biomass supply, charcoal and bio-oil market status and logistics should be taken into account.

## 3. Concept description-methodology

A number of different options have been proposed in the literature regarding the location of the pyrolysis and the gasification/biorefinery plants. The present work is focused on the approach

of the "decentralized feedstock pretreatment and centralized bio-refinery" concept [8]. The biomass produced in a decentralized rural farm community is converted to bio-oil in a local fast pyrolysis plant. The liquid product is subsequently supplied to a large central plant (i.e. gasification plant) where its final processing/utilization takes place.

The economic analysis performed has the purpose of determining the conditions under which the decentralized conversion of biomass to bio-oil via fast pyrolysis can actually reduce total fuel acquisition costs for a central gasification/bio-refinery plant. For the purpose of the analysis a circular area S of radius $R_n$-source of homogenously distributed biomass (i.e. energy crops) of surface density (dry t/ha) $\delta$ and *a* central plant C are considered (see Fig. 1). The direct distance between the center of the circular area *P* and the central plant C is equal to *D*. The investigation is based on the comparison of two different scenarios: In the first one, the biomass of each internal point (field) of the circular surface S is directly transported to the central plant C. In this case, the total fuel acquisition cost equals to the sum of the purchase plus the road transportation cost of the biomass. In the second scenario, the biomass inside S is firstly transported from every local field to P, where it is converted to bio-oil in a fast pyrolysis unit. The produced bio-oil is afterwards transported to C. The total fuel acquisition cost of this scenario includes the cost of purchasing and transporting the biomass to P, the cost of producing bio-oil in the fast pyrolysis unit as well as the cost of transporting it to C. The capacity of the biomass considered is a core parameter of the evaluation, since it greatly influences the capital cost of the plant and therefore the cost of bio-oil production. Annual biomass feedstock rates corresponding to 20 and 80 dry t/h pyrolysis plant capacities have been frequently reported in previous economic analyses [6,9,16,37].

Owed to its higher energy density, the specific transportation cost of bio-oil is lower than the respective cost of biomass. Therefore, as the distance *D* increases, the total cost of the second scenario (involving fast pyrolysis) tends to diminish relatively to the total cost of the first (involving direct biomass transportation).

One of the goals of the economic evaluation of this work is to determine the existence of a realistic direct critical distance $D_{cr}$ between the points P and C, beyond of which the second scenario is always more beneficial in comparison to the first. Given a value of $D_{cr}$, it follows that fuel transport costs for the central unit can be optimized when biomass from sources situated inside the boundaries of the circle with radius $D_{cr}$ and center C is transported directly to the central gasification plant and any biomass from sources externally located is firstly converted into bio-oil in fast pyrolysis units. The main parameters affecting the value of $D_{cr}$ include the biomass surface density, the capacity of the biomass feedstock within S as well as the characteristics of the species considered.

The analysis is carried out in two steps. Firstly, a methodology for the estimation of the transportation cost of biomass and bio-oil is introduced, taking into account the special product characteristics (density, heating value, moisture) and means of transportation used. These costs refer to:

1. Transportation of biomass from the source (every field-point of S) to its center P.
2. Transportation of biomass from the source (every field-point of S) to a location C situated in its exterior.
3. Transportation of bio-oil from one location P to another C.

All transportation costs are assumed to be marginal, which means that they are estimated on the basis of a net present value equal to zero. This means that the minimum transportation costs are evaluated in each case, since the net profit of the organization/company charged with the fuel transportation is assumed equal to zero. In a realistic situation, this assumption would mean that the transportation capital (trucks, facilities, etc.) are either property of the owner of the fast pyrolysis or the gasification plant, who is also responsible for the coverage of all the operating costs (driver payments, fuel, truck maintenance, utilities), or is owned by self-employed truck drivers. In any other case, if for example an external transportation company is contracted for transporting the biomass/bio-oil, the costs should be higher than estimated by the methodology followed in this study, in order to account for the net profit of the company. The approach employed has been adopted in various other transport cost-related studies [9,16,51–53].

Secondly, the production cost of bio-oil is estimated for varying values of plant size, biomass surface density and purchase price, though a complete techno-economic analysis of a fast pyrolysis unit located in P. A model predicting fast pyrolysis products distribution and their corresponding heating values is employed in order to estimate the energy efficiency of the process and the by-product char and gases utilization requirements.

The final fuel acquisition costs of each scenario (€/GJ) are calculated in each case for a range of values of the distance *D*. The critical distance $D_{cr}$ is the value of *D* for which the two costs are equal. Practically, any type of biomass can be selected for fast pyrolysis processes, with nearly 100 different species having been tested, ranging from agricultural wastes to energy crops and solid wastes [15,54]. The present analysis is carried out for two biomass species, SRC willow woodchips and miscanthus, which are representative of woody and herbaceous biomass of high and lower energy density respectively [3].

## 4. Biomass and bio-oil transportation costs

The transportation cost of biomass and bio-oil by truck has been estimated and reported in various studies [9,39,52,53]. It is shown that this cost is connected with the transportation distance by a linear function and is commonly expressed by using a fixed cost FC (€/t) and a variable cost VC (€/(tkm)) coefficient, which are independent and dependent of the transportation distance respectively [9,52]. Therefore the total specific cost (€ $t^{-1}$) is given according to the equation:

$$TC = FC + VC \times D \tag{1}$$

In the above equation, *FC* signifies the fixed cost (€/t) and *VC* the variable cost coefficient (€/tkm), while *D* is the direct transportation distance of the biomass. This means that when biomass is transported in a direct distance, one part of the total cost depends purely on the quantity (tonnes) of biomass ($FC \times t$) while another part depends not only on the quantity, but also on the distance ($VC \times t \times km$). In the present study, it is assumed that biomass is transported by trucks. For the case of bio-oil, both options of tanker trucks and pipeline transportation are examined.

### 4.1. Estimation of biomass and bio-oil transportation cost

In order to determine the type of truck used in each case of transportation, special weight and volume limitations for different biomass types and for bio-oil should be taken into consideration because of their varying density. European Union regulations limit the Gross Vehicle Weight Rating (GVWR) of articulated trucks to 40 t (in the US this limit is 36.3 t [2]), with equivalent restrictions on vehicle dimensions, which cannot exceed the size of $4 \times 2.55 \times 16.5$ m. The above regulations pose an upper limit to the net payload that can be carried by the transport vehicles.

The maximum cargo volume is thus limited to about 150 $m^3$ and the payload to 29 t for the biggest trucks available, for example, on the UK Ministry of Transport freight Best Practice

guide [55]. The criterion for selecting the appropriate truck type is the maximization of the payload, since it leads to minimization of the roundtrips and therefore of vehicle and driver requirements.

**Table 1**
Non-driving time for woodchips, miscanthus and bio-oil transportation [53].

| Feedstock type | Woodchips[a] | Miscanthus[a] | Bio-oil[b] |
|---|---|---|---|
| Roundtrip time | Minutes | Minutes | Minutes |
| Loading | 34 | 36 | 15.53 |
| Load covering | 10 | 10 | 15 |
| Unloading | 10 | 18 | 15.53 |
| Weighing | 10 | 12 | 10 |
| Idle time[c] | 10 | 10 | 10 |
| Total $t_{rest}$ | 73 | 86 | 66 |

[a] A 5 $m^3$ front end loader and an adapted front end loader are used for loading of woodchips and miscanthus. A walking floor and an automated granty crane are used for unloading woodchips and bales respectively. Additional time is needed for covering the load to prevent dust spillage and for weighing the truck.

[b] Bio-oil is loaded and unloaded using six parallel 200 mm diameter pipes. The capacity of loading and unloading is calculated by Hagen Poiseuille law of Newtonian liquids, using bio-oil property values given from Dynamotive. An allowance is for connecting and disconnecting hoses and for weighbridge operations.

[c] An allowance of 10 min of idle time per roundtrip has been made in order to make up for unscheduled delays.

**Table 2**
Transportation modes and cost equations.

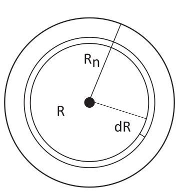
**Single distance transportation**




$FC\times Bio+VC\times D\times Bio$ (t1)

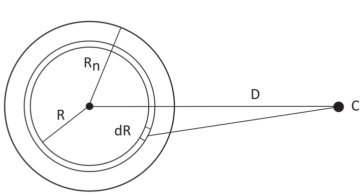
where Bio stands for the biomass quantity to be transported (t)

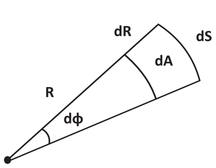
**Transportation from circular surface to center**




$C_1\times R_n^{\,2}+C_2\times R_n^{\,3}$ (t2)

**Transportation from circular surface to external point**




$C_3\times R_n^{\,2}+C_4\times\int_0^{2\pi}\int_0^{R}\sqrt{R_n^{\,4}+R_n^{\,2}D^2+2R_n^{\,3}D\cos(\varphi)}\,dR\,d\varphi$ (t3)

Given the above limitations, it is concluded that bio-oil and woodchips, having a density of 1.2 t/$m^3$ and 0.22 t/$m^3$ [55] respectively, can be transported by a 38 t articulated truck with a semi-trailer of a payload of 29 t [55]. For miscanthus of density of about 0.14 t/$m^3$ [16], a 32 t rigid truck, having a payload of 20 t should be used [55]. The above assumptions are in general agreement with these followed in similar studies, such as [52] (woodchips payload = 40 t-van, straw payload = 20 t with flatbed truck), [56] (bales miscanthus giganteus payload = 18.36 t), [39] (bio-oil payload for tankers = 30.5 and 24 t), [9] (bio-oil payload 36 t for liquid tank truck), and [57] (cotton stalks and almond tree prunings payload for trucks = 25 t).

The single distance transport cost is defined as the cost of transporting a product (biomass/bio-oil) from a starting point to a destination. The total number of annual roundtrips required is calculated given the annual product capacity and the payload of the trucks. The time needed per roundtrip is divided into two parts. The first part is made up of the driving time, dependent on transportation distance and average truck speed. A winding road factor $w_f$ is applied to account for the indirect routes of the road grid [39,57]. The average truck speed must be in the range of speed limits regulations. It also depends on the status of the road grid used (i.e. rural/national roads). The second part of the total roundtrip time $t_{rest}$ consists of time needed for other transport related procedures besides driving such as loading and unloading, weighing and covering the load. This amount of non-driving time has been reported for woodchips, miscanthus and bio-oil by Rogers and Brammer [53], based on literature data from [58,59]. Woodchips and miscanthus are loaded with a front and an adapted front end loader [53]. Bio-oil is fed to and extracted from the tanker truck using parallel 200 mm diameter pipes. The loading capacity is calculated by Hagen Poiseuille law using property values given from Dynamotive [53,60]. An amount of idle time (unexpected delays) is also taken into account. The non-driving time $t_{rest}$ and its components are summarized in Table 1. From the total annual operating hours, given a specified value of man hours and for a certain number of delivery days, the number of drivers to be employed is estimated. The number of trucks is determined by the recommended annual mileage for each truck type while at the same time considering a daily delivery time upper limit equal to 12 h [53].

The total single distance transportation cost for a distance of $D$ km is given by a linear equation (2). In order to calculate the biomass collection cost from each point of a circular surface of radius $R$ to its center or to a point situated outside its boundaries, the respective surface integrals of the above equation are calculated (Eqs. 2 and 3). The transportation scenarios and the equations used to determine the respective costs are summarized in Table 2.

All transportation parameters, together with costs related to truck capital and maintenance, insurance and road taxation, as well as fuel consumption for the trucks selected in each case are presented in Table 3. The values for the technical characteristics (maximum payload, fuel consumption) cost variables and other economic parameters (capital and maintenance cost, fuel consumption, insurance, etc.) involved are taken based on reported values from representative actual trucks [55]. For comparison, as far as the truck capital cost is concerned, in [57] the authors use a value of 120 k€ for a 40 t payload truck, while in [3] a cost of 145–160 k€ is reported for a 20–22 t truck and trailer. An even lower value of 79 k€ is reported in [61] for a 42 t truck.

The primary parameters of the methodology used for the estimation of the transportation cost are graphically depicted in Fig. 2.

### *4.2. Transportation costs results and discussion*

Assuming an average speed of 50 km/h, the single distance transportation specific cost of willow woodchips, miscanthus bales

**Table 3**
Economic and transportation parameters for woodchips, miscanthus and bio-oil.

| *Feedstock type* | **Woodchips** [3] | **Miscanthus** | **Bio-oil** [5] |
|---|---|---|---|
| Moisture content | **30%** | **15%** | **25%** |
| *HHV* | **18,400 MJ/kg (d.b.)** | **17,600 MJ/kg (d.b.)** | **17,000 MJ/kg (a.r.)** |
| **Economic parameters** | | | |
| Truck type[55] | 38 t truck with semi trailer | 32 t rigid truck | 38 t truck with semi trailer |
| Truck capital cost [55] | 110,000€ | 100,000€ | 110,000€ |
| Interest rate [55] | 7% | 7% | 7% |
| Project life (service life of truck) [55,57] | 6 years | 7 years | 6 years |
| Mileage [55] | 112,654 km | 64,374 km | 112,654 km |
| Maintenance and repairs [55] | 15% of capital | 19.5% of capital | 15% of capital |
| Insurance and taxes [55] | 6% | 5.7% | 6.0% |
| Driver earnings [55] | 26,000 € | 26,000 € | 26,000 € |
| Fuel consumption [55] | 0.41 L/km | 0.40 L/km | 0.41 L/km |
| Fuel price [62][1] | 1.5 €/L | 1.5 €/L | 1.5 €/L |
| **Transportation parameters** | | | |
| Truck payload [55] | 29 t | 20 t | 29 t |
| Average speed $u$ [63][a] | 30–80 km/h | 30–80 km/h | 30–80 km/h |
| Winding road factor [53,57][b] | $\sqrt{2}$ | $\sqrt{2}$ | $\sqrt{2}$ |
| Annual delivery days [53][c] | 230 days/year | 230 days/year | 230 days/year |
| Daily driver shift [64] | 8 h | 8 h | 8 h |
| Max daily delivery time [53] | 12 h | 12 h | 12jh |

[1] Diesel oil price, European energy portal website.
[a] Average transportation speed is based on legislation and road grid status: For national roads maximum speed limit for trucks is $u = 80$ km h$^{-1}$ in most EU nations [63]. For rural areas a speed of $u = 30$ km h$^{-1}$ (rural area) is assumed (decentralized transportation from biomass source to pyrolysis plant). This speed value was assumed based on data provided by [65] for travel speeds on 2 lane highways, graveled county roads and logging roads. For central transportation (direct biomass and bio-oil transportation) a weighted average speed is assumed $u = (R_n/R_o)u_1 + (R_o - R_n/R_o)u_2$ where $u_1 = 30$ km/h, $u_2 = 75$ km/h.
[b] This assumption is made on the basis that the actual route taken between a feed source and the feed conversion facility in a grid of roads would run along two sides of a right-angled isosceles triangle.
[c] The number of delivery days is estimated after non-delivery days (weekends, holidays, etc. are subtracted).

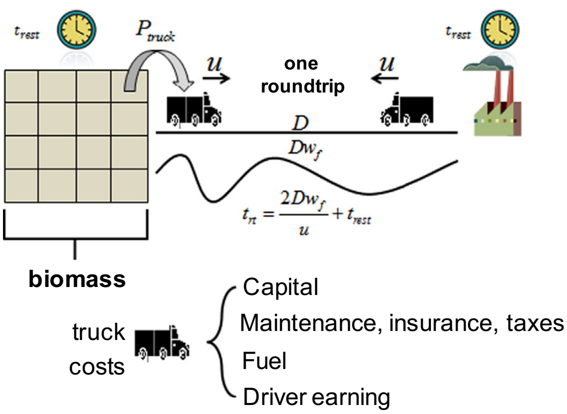



**Fig. 2.** Graphic representation of the model used for transport cost estimation.

and bio-oil, as well as the specific collection cost from a circular surface of radius $R$ to its center for woodchips and miscanthus is shown in Fig. 3a and Fig. 3b.

The HHV and the density of each product have a great impact on the transportation cost, since for the same amount of energy content, more roundtrips are needed for the delivery of products of lower energy density. Consequently, more operating hours and trucks are required, thus increasing capital and operating costs. As a matter of fact, the specific transport cost is lowest in the case of bio-oil and highest in the case of miscanthus.

Rogers and Brammer [53] introduce a zone costing approach for transport cost estimation, based on the noted strong connection between the specific transportation cost and the maximum number of daily roundtrips carried out. The values from different studies on biomass and bio-oil transport are listed in Table 4.

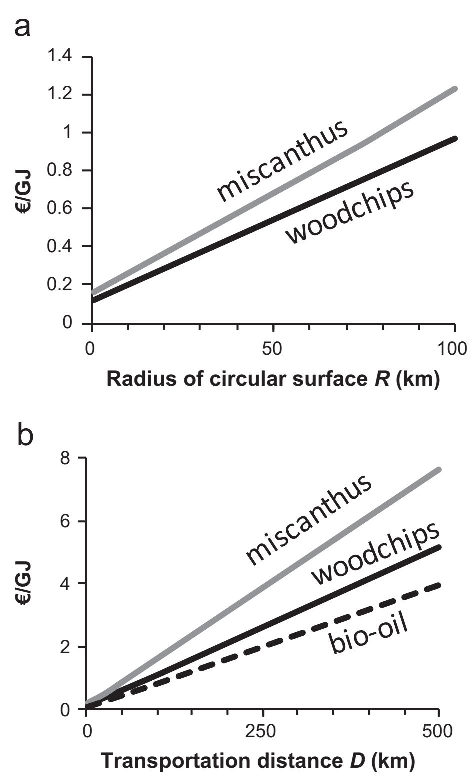



**Fig. 3.** (a) Specific transportation cost from a circular surface of radius $R$ to its center for woodchips and miscanthus. (b) Single distance specific transportation cost of woodchips, miscanthus and bio-oil for a distance $D$.

### *4.3. Pipeline vs truck transportation of bio-oil*

The transportation of bio-oil by pipeline has been investigated by Pootakham and Kumar [9]. It is shown that it is dependent on bio-oil capacity. For 500 m$^3$/day and for a distance of 100 km the fixed and variable cost components of transportation are 0.0423 \$/m$^3$ and 0.1201 \$/m$^3$ respectively. For other capacities the transportation costs are given in Table 5.

**Table 4**
Biomass and bio-oil transportation costs as estimated from previous studies and for the current study.

| Commodity | Pootakham/Kumar [9,52] | Rogers and Brammer [53] | Bridgwater [39] | Present study |
|---|---|---|---|---|
| Biomass | Woodchips<br>FC=2.80 €/t<br>VC=0.05 €/(tkm)<br>Straws<br>FC=4.08 €/t<br>VC=0.09 € /(tkm) | Woodchips<br>0–11 km: 0.17 €/GJ<br>96–224 km: 1.11 €/GJ<br>Miscanthus<br>0–11 km: 0.23 €/GJ<br>87–215 km: 1.35 €/GJ | | Woodchips:<br>FC=0.85 €/t<br>VC=0.12€/(tkm)<br>Miscanthus:<br>FC=1.36 €/t<br>VC=0.21 €/(tkm) |
| Bio-oil | Liquid tank truck<br>FC=3.84 €/t<br>VC=0.03 €/(tkm)<br>Super B-train tank trailer<br>FC=5.71 €/t<br>VC=0.05 €/(tkm) | 0–11 km: 0.17 €/GJ<br>96–224 km: 1.27 €/GJ | FC= 4.29 €/t<br>VC=0.039 €/(tkm) | FC=0.76 €/t<br>VC=0.12 €/(tkm) |

**Table 5**
Fixed distance cost (FC) and variable distance cost (VC) coefficient values for bio-oil pipeline transportation [9].

| Capacity of pipeline transporting bio-oil (t/h) | FC (€/t) | VC (€/(tkm)) |
|---|---|---|
| 7.8 | 0.0987 | 0.2864 |
| 12.5 | 0.0686 | 0.2039 |
| 23.45 | 0.0451 | 0.1176 |
| 50 | 0.0281 | 0.0682 |
| 100 | 0.0198 | 0.0418 |

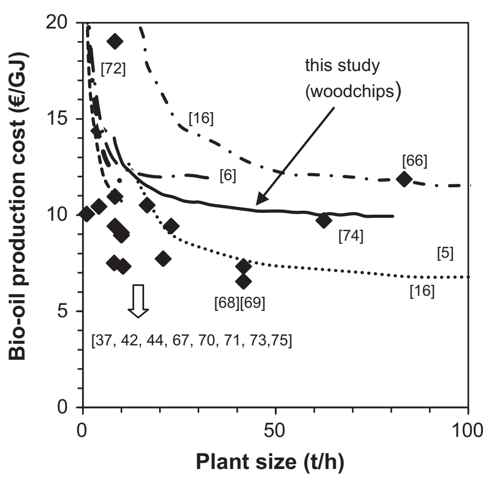



**Fig. 4.** Reported bio-oil production costs from several studies in the literature [16,37,42,44,66–75].

Given the data from Table 5, the specific cost €/t of bio-oil transportation by pipeline is plotted for various capacities against the respective cost of truck transportation. While the specific cost of pipeline transport is dependent upon the capacity of bio-oil, the cost of truck transport is fixed regardless of the amount of bio-oil to be delivered. Assuming a bio-oil yield of about 65%, it follows that for the bio-oil flow rate corresponding to fast pyrolysis unit biomass capacities under 23 dry t/h, it is beneficial to carry out the transportation by trucks, while for higher capacities the option of pipeline becomes increasingly advantageous.

## 5. Bio-oil production cost

The production cost of bio-oil has been investigated in several studies for different kinds of biomass, reactor capacities and configurations. According to estimates reported in [66], it ranges between 69 and 414.34 €/t. A number of literature data on the reported bio-oil production costs of fast pyrolysis units for various feed capacities and reactor types gathered from various studies [16,37,42,44,66–75] are plotted in Fig. 4. It should be noted that these studies do not always follow the same approach on the definition of the total capital investment, since in some cases cost components such as land and site preparation are not included in the value of the capital cost assumed. Moreover, due to the chronological difference among the studies (covering a span from the early 90 s to the late 2000 s), the effect of the developing maturity of the technologies examined (reactors, etc.) on the capital costs is not negligible. Furthermore, the values of some major economic assumptions (such as labor and biomass purchase cost) differ significantly from study to study. As a result, great care should be taken before establishing a correlation between bio-oil production cost and pyrolysis plant capacity or directly comparing the results from different investigations.

Most of the studies included in the present work concern pyrolysis plants with capacities lower than 20 dry t $h^{-1}$. On the other hand, very few investigations on larger units (above 40 dry t $h^{-1}$) have been conducted. As can be seen from Fig. 4, a high number of studies indicate that the cost of producing bio-oil ranges from 4 to 10 € $GJ^{-1}$ (i.e. [16,37,42,69]), while others estimate values of up to 18–19 € $GJ^{-1}$ [68,72].

The price of biomass purchase, ranging from 30 to 90 €/t [5,17,37,77], as well as the fast pyrolysis plant scale, highly influence the bio-oil production cost. The effect of the plant scale on the economic feasibility of bio-oil production plants has been examined in many studies [5,6,16,39,42]. However, there is an upper limit of the plant capacity beyond which the benefits become less significant [5,6,16]. According to the curves plotted in Fig. 4, this limit is estimated between approximately 10 and 20 dry t $h^{-1}$ biomass capacities. Despite the expected economic benefits from large fast pyrolysis plants, it should be noted that the continuous operation of large scale commercial bio-oil production facilities has not been yet demonstrated and there are unresolved issues regarding the practical viability of the heat transfer to the reactor [5,18,23,37].

### 5.1. Biomass pretreatment facility

Before the main thermo-chemical conversion takes place, the raw biomass feed to the plant should be appropriately prepared. The biomass pretreatment facility is an important part of a fast pyrolysis unit, taking up a significant percentage of capital and operating costs [6,16,37,66]. Its basic tasks include screening the incoming biomass, feedstock storage, drying and grinding [6,28,39]. The storage facilities should be able to provide a buffer zone for non-delivery periods (for example in seasonally harvested feed-stocks) and assure a steady fuel flow to the reactor [6,39]. The biomass feedstock delivered to the pyrolysis plant is usually in the

form of chips or bales which facilitate its transportation. Its initial moisture can be between 50 and 60% (wet basis) [23,28], depending on the fuel type. During its storage, it is possible to decrease its moisture content by passive drying (through sunlight and ambient air) storage to 3–30% [23,28]. However, size reduction of the biomass to fine particles of 1–2.5 mm size [6,37,78], as well as further drying to levels of moisture lower than 10% ( and of about 7%) w/w are necessary [6,28,37,76] in order to achieve the high heating rates required for the maximization of the bio-oil yield during the reaction. Too much moisture in the initial fuel can lead to lower heating values of the produced bio-oil, since almost all of the moisture of the biomass appears in the pyrolysis liquids [28]. At the same time, water contents influence the bio-oil's physical properties such as chemical stability, viscosity, corrosiveness and pH [28]. The above reasons make the drying process of the initial biomass very important, since it is difficult to remove the water content from the pyrolysis oil by conventional methods (although it is possible to reduce water contents by selective condensation) [79].

It has been experimentally shown that smaller feedstock particle size distributions promote the increase of the yields of the liquid products against the products of solid and gaseous phase [13,78]. Experiments conducted in [78] concluded that this is mainly because of the increased heating rates experienced by finely ground biomass particles.

Both grinding and drying consume a significant amount of electricity [37], which can either be provided on-site by combustion of the by-product char, permanent gases and additional biomass or purchased from the power grid. The drying of the biomass fuel, initially having a moisture content of about 15–30% w/w, demands a certain amount of heat which is provided by by-product utilization [5,37]. Other parts of the pretreatment facility include fuel reception and handling equipment, such as ground hoppers and conveyors [6].

### 5.2. Fast pyrolysis facility

The fast pyrolysis reactor is a primordial part of the fast pyrolysis plant and represents about 10–15% of its total capital cost [5]. As of today, many different reactor types and configurations have been proposed. These include the bubbling and circulating fluidized bed, ablative, auger, entrained flow, rotating cone, transported and vacuum moving bed reactors [23].

The various reactor types employed for fast pyrolysis processes as well as their operational properties and performance parameters have been extensively discussed [5,18,23,80]. A brief summary of their advantages and disadvantages together with some typical liquid yield values as described in the literature is given in Table 6.

Lehto et al. [40] gathered information on bio-oil production processes in 2012 with capacities above 10 kg/h. The data provided from this study, combined with data from [5,81] referring to industrial fast pyrolysis applications is presented in Fig. 5. The applications are sorted by feed capacity, reactor type and their operational status.

The bubbling, circulating fluidized bed (BFB and CFB) and at a somewhat lesser extent the auger/screw reactors are currently the most popular and considered commercially viable for large scale use [5,15,37,42], as also reflected on the fast pyrolysis applications presented in Fig. 5.This is attributed to their higher bio-oil yields, technical maturity and ease of up scaling. The use of other reactor types is for the time being fairly limited and mainly aimed at demonstration and laboratory purposes [15,18]. However, up until now no reactor technology has been conclusively determined as ultimately superior, since each category exhibits some advantages while at the same time encountering technical challenges [5,15,18,23]. However, because the bubbling fluidized bed applications are for the time being relatively more popular than others, the BFB configuration is considered in the present study Fig. 6.

Inert gas species ($N_2$ or permanent gases) are used for the bed fluidization. Process heat is supplied to the reactor by circulating

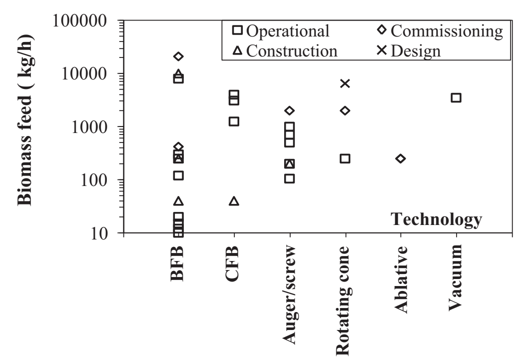



**Fig. 5.** Existing pyrolysis technologies vs. plant capacity.

**Table 6**
Overview on pyrolysis reactors types [5,18,23,80].

| Reactors types | Advantages | Disadvantages |
|---|---|---|
| Fluidized bed reactor Bio-oil yields: 70–75% (wood) | Good temperature and residence time control, simple construction, efficient heat transfer, easy scalability, mature technology, good and consistent performance, high bio-oil yields, char is recycled and can be utilized, heating can be achieved in various ways | Small particle size distribution needed (2–3 mm), careful design for heat exchange and liquid collection systems needed, good char separation necessary, larger equipment and cost unproven heat transfer at large scale, difficult aerosol capture |
| Circulating fluidized bed reactor<br>Bio-oil yields: 70–75% (wood) | Good temperature control, larger particle sizes possible, operation at large scale, mature technology | Complex hydrodynamics, smaller char particle size can lead to high char content in bio-oil, unproven heat transfer at large scale, no byproduct char |
| Rotating cone reactor<br>Bio-oil yields: 60–70% | Operation based on centrifugal forces, smaller carrier gas requirements in the reactor | Relatively recent technology, no byproduct char, gas needed for char burn-off and sand transport, complex integrated operation of reactor subsystems needed |
| Entrained flow reactor<br>Bio-oil yields: 50–55% | Simple technology, good scale up | Unsuccessful developments due to poor heat transfer, increased has flows required, large equipment, problematic liquid collection, lower liquid yields |
| Vacuum reactor<br>Bio-oil yields: 35–50% | Lower temperature required, larger particle sizes possible, no carrier gas requirement | Too high residence time-unfavorable for effective fast pyrolysis, low liquid yields, complex process large equipment |
| Ablative reactor<br>Bio-oil yields: 60–75% | Larger particle sizes required, no inert gas required, intensive system, lower temperature required, smaller equipment, efficient liquids collection | Low reaction rates, high construction and scaling cost, more complex because reactor is mechanically driven |
| Auger reactor<br>Bio-oil yields: 30–50% (wood) | Compact structure, no carrier gas needed, lower reaction temperatures required, suitable for heterogeneous or materials difficult to handle | Moving parts in hot temperature zone, difficult to achieve low residence times, unproven heat transfer at large scale, lower liquid yields, higher char yields |

flue gases produced from the permanent gases and char combustion [5,23,37].

Char separation is performed by the use of one or more high efficiency cyclones [5,6,37]. The quenching of volatile vapors is carried out by direct cooling, though injection of cooled bio-oil or a solution of immiscible hydrocarbons [5]. It has been reported that indirect heat exchange can lead to deposition of lignin-derived components, causing blockage in pipelines and deterioration of heat exchange surfaces [5]. Moreover, electrostatic precipitators (ESPs) need to be employed for efficient aerosol capture [5]. Bio-oil is highly corrosive, its pH ranging around 2–3 [5,40,82], and should be properly stored in tanks made of stainless steel or plastic [26]. An increase in its viscosity over time has been observed, while another phenomenon known as aging involves the continuation of slow secondary pyrolysis reactions [4,5,26]. Diebold [83] reports that the aging effect occurs much faster at higher temperatures, with the viscosity increase rate varying more than four orders of magnitude for hardwood and softwood bio-oils.

Fast pyrolysis is a slightly endothermic reaction. A multitude of values concerning the heat input required for its completion have been reported in the literature. In [1] experiments of fast pyrolysis of a variety of feedstock types (pruce, poplar, straw, etc.) concluded to values between 0.207 and 0.437 MJ $kg^{-1}$. In [6] value of 1.5 MJ $kg^{-1}$ of dry biomass feed is reported. In [21], the heat of reaction is reported equal to 2.5 MJ/kg of bio-oil produced. In [84], two semi-empirical equations are proposed in order to predict the heat of the reaction based on its moisture and ash content. There are many difficulties concerning the accurate estimation of the process heat, which are related to the complex nature of the chemical reaction [85]. The necessary heat stream should be provided to the reactor in a temperature of at least 500 °C. Further heat is necessary for reheating the fluidizing medium, which in the present work is considered to be composed of permanent gases produced from the process. As previously stated, additional heat is needed for drying the biomass. These heat requirements are covered by partial combustion of the permanent gases and char. Any char that remains unused can be either combusted in a steam generation cycle in order to cover the electricity required for the facility or sold [6].

### 5.3. Product yields and properties prediction model

Various efforts have been made to model the process of fast pyrolysis with the aim to predict the yields of the final products as well as their composition and energy content. The importance of accurately calculating these values is substantial in the scope of a techno-economic analysis of a unit, since it allows for better estimation of parameters related to the total bio-oil production cost, such as the energy efficiency of the process, the amount of the heat necessary for its completion as well as the by-product combustion requirements. Additionally, precisely predicting the elemental composition of bio-oil is paramount when scenarios involving its use for chemical syntheses and bio-fuels production are economically evaluated.

Nonetheless, there is some substantial difficulty of effectively modeling fast pyrolysis [86]. This difficulty originates partially from the limited knowledge of its exact reaction mechanism as well as from its high sensitivity to the reaction conditions (temperature, heating rate, particle size, reactor type, residence time, etc.) and feedstock processed (chemical composition, moisture, ash content) [15,28]. The yields of char, bio-oil and permanent gases and their respective compositions and heating values are often given experimental indicative values [37]. Another approach is to model the bio-oil mixture with a selection of representative organic compounds [14,37]. These methodologies generally aim to maintain mass balance closure, without investigating any underlying relation between the properties of the products (yields, elemental compositions and heating values) and the properties of the initial biomass.

The characteristics of SRC willow and miscanthus considered in the present study are retrieved from [3]. The high heating values and compositions of the pyrolysis products for each case are calculated though the implementation of a fast pyrolysis model. This model encompasses a set of semi-empirical equations pertaining to the ultimate and proximate analysis of the initial biomass and the reaction temperature [29]. The equations were developed by regression from a large number of experimental data under various conditions [29]. The yields of bio-oil, char and permanent gases are given experimental values reported in [87], which are in accordance with literature data given in [5,24,88,89].

Additional equations of mass and elemental balance are supplemented to the model. All ash and moisture content found in the initial biomass is assumed to accumulate to the char residue and to the bio-oil mixture respectively. The *HHV* of the permanent gases is directly calculated from their composition, as is derived from the model. The main characteristics of SRC willow, miscanthus and their pyrolysis products as derived from the model are summarized in Table 7. The *HHV* of char and bio-oil is calculated from their ultimate analysis by correlations found in the literature [90,91], as presented in Table 8.

In Fig. 7 the main mass and energy (fuel basis) flow rates for a woodchips fast pyrolysis facility of 20 dry t/h is presented, as estimated by an Aspen Plus™ [92] model that was developed. Additional information given is the heat input requirements for the pyrolysis reaction, the recycle gas reheat as well as for the drying of the woodchips. The amount of char that is utilized for the process is calculated assuming that the temperature of the flue gases exiting the facility is equal to 180 °C. The electricity consumption for drying and grinding the biomass, as well as additional electricity loads of the facility are also included (see the following chapter).

### 5.4. Total capital investment cost

The calculation of the TCI is based on the calculation of the Direct Plant Cost (DPC) of the pyrolysis plant. The Direct Plant Cost includes equipment purchase and installation. From the DPC and by a series of assumptions about the various cost components distribution, the TCI is estimated. These assumptions are summarized in Table 9 [37,93].

As described above, a fast pyrolysis unit consists of two primary facilities. The TPC for various plant capacities for each one is

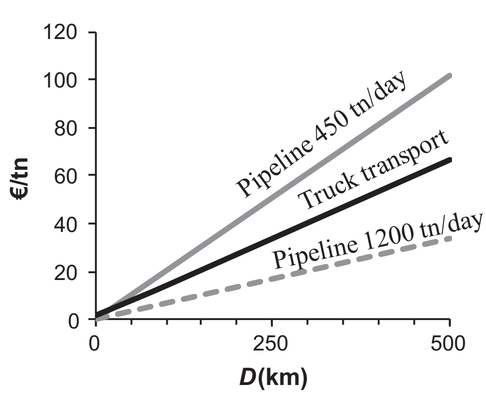



**Fig. 6.** Truck vs pipeline transportation specific cost for bio-oil capacities corresponding to biomass capacities of approximately 20 and 80 dry t/h, assuming a bio-oil yield of 65% w/w. The figures are plotted based on data from Table 5 and from the methodology of chapter 3.1.

**Table 7**
Biomass, bio-oil, char and permanent gases characteristics and their respective yields assumed in the present study.

| | Biomass | Bio-oil | Char | Permanent gases |
|---|---|---|---|---|
| | | SRC willow (30% moisture) | | |
| Yield *HHV* (w.b.) | –<br>12.9 MJ/kg | 71%<br>15.4 MJ/kg | 16%<br>25.2 MJ/kg | 13%<br>6.5 MJ/kg |
| | | Miscanthus (15% moisture) | | |
| Yield *HHV* (w.b.) | –<br>15 MJ/kg | 69%<br>17 MJ/kg | 19%<br>22.1 MJ/kg | 12%<br>6.5 MJ/kg |

**Table 8**
Equations for predicting the HHV of biomass, bio-oil and char (MJ/kg).

| Product | High heating value |
|---|---|
| Biomass [91] | $HHV_{db}=0.00355C^2-0.232C-2.230H+0.0512CH+0.131N+20.6$ |
| Bio-oil and Char [90] | $HHV_{db}=0.3491C+1.1783H+0.1005S-0.1034O-0.0151N-0.0211A$ |

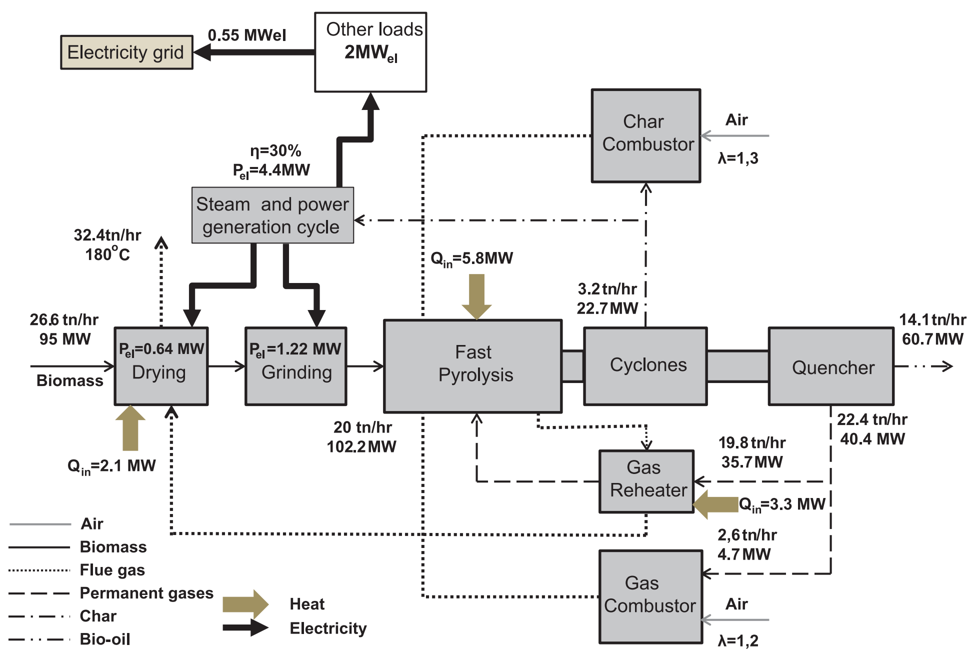



**Fig. 7.** Woodchips facility block diagram including mass-energy (fuel basis), heat and electricity flows.

estimated by equations given by Rogers and Brammer in [6] based on regression from data derived from past studies [39,42,70].

The cost of the pretreatment plant was derived from surveys on US timber fired power stations and straw co-firing as well as straw-to-ethanol plants [6,58,59,94]. There is very little difference between the cost of woodchips and miscanthus pretreatment facility, so the same regression equation can be used without significant error. The pyrolysis facility cost equation involves the reactor, liquids collection and storage system and excludes site purchase, ground clearance, site access and consenting costs and is modified accordingly. The equations employed are used for capacities of up to 200 dry t/day [53]. For larger plant sizes multiple 200 dry t/day units are assumed. If the remaining char of the process is to be utilized for steam generation in order to produce electricity, an additional steam and power generation unit (SPGU) as well as a cooling tower (CT) is required. The DPC of these two elements is reported in [16], using cost data and scaling factors retrieved from [37,95–97]. The SPGU consists of an economizer, boiler and a turbine. The electricity produced was estimated on the assumption that the thermal efficiency of the power generation unit would be approximately similar to that of pulverized coal thermal plants of equivalent size (∼50 to 60 $MW_{th}$ thermal input).

**Table 9**
Capital cost allocation of fast pyrolysis unit [37,93].

| | |
|---|---|
| **Direct plant cost (DPC) sum of TPC:** | |
| Equipment, buildings erection, piping etc. | 66.5% |
| Warehouse | 3% |
| Land | 4% |
| Site development | 3% |
| **Indirect plant cost (IPC) sum of DPC:** | |
| Engineering and Supervision | 8% |
| Construction | 10% |
| Contractor's fee | 5% |
| Contingency | 8% |
| TPC = DPC + IPC | 90% of TCI |
| Working capital (WC) | 10% |
| **Total capital investment (TCI)** | TPC + WC |

In the literature values ranging from 30 to 40% are commonly reported [98–100]. In the current study, a thermal efficiency of 30% is considered Fig. 8.

The equations used are summarized in Table 10. The specific DPC (per dry t of biomass feed) for the major capital cost components of the fast pyrolysis unit (pretreatment and pyrolysis plant, SPGU and CT) are plotted against various biomass capacities in Fig. 9. All currency values (in equations and charts) are converted in 2012 €.

The specific total DPC (k€/(dry t/h) of biomass feed) of the pyrolysis unit is much higher for smaller units and is decreased for larger ones. This is owed to the great economy of scale benefits linked to the pyrolysis and biomass pretreatment facility. The impact of these benefits is substantial for units of up to 20 dry t/h capacities and gradually decreases when the plant capacity further increases.

The pyrolysis facility is the major cost component of the installed capital of the pyrolysis plant. The DPC of the biomass pretreatment plant is about 20–30% of the total DPC. The corresponding costs of steam and power generation and cooling tower are higher for smaller units (with capacities under 10 dry t/h).

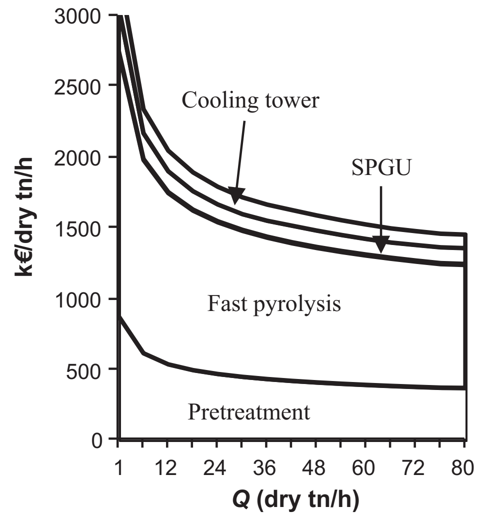



**Fig. 9.** Biomass pretreatment and pyrolysis plant. SPGU and CT specific DPC (k€/dry t) for biomass capacities ranging from 1 to 80 dry t/h.

### 5.5. Operation and maintenance cost

The O&M includes labor, electricity, overhead production, insurance, maintenance and fuel costs. The number of personnel employed is estimated by the Wessel equation [101], for semi-continuous operating conditions and considering five processing steps. The average salary is based on gross annual earnings in the German industry [102]. Overhead labor costs equal to 60% of labor [37,66,77], while maintenance is 2% of equipment [93].

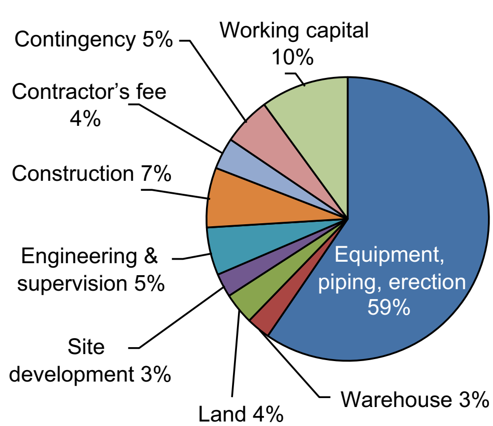



**Fig. 8.** Percentage contribution to TCI of various cost components for base case plant.

**Table 10**
Fast pyrolysis unit total plant cost estimation equations and assumptions [6,16].

| |
|---|
| **Pretreatment plant** |
| $TPC_{pret} = 422.3x + 1125.4$ (k€) [53] |
| **Pyrolysis plant** |
| $TPC_{pyr} = 3404.2\ \ln(\frac{x}{24}) - 8301$ (k€) [53] |
| **Steam and Power Generation Unit (SPGU)** |
| $DPC_{SPGU} = 2612(\frac{x}{20.83})^{0.7}$ (k€) |
| **Cooling tower unit and other utilities** |
| $DPC_{CT} = 2684(\frac{x}{20.83})^{0.78}$ (k€) |
| where $x$ is plant capacity, dry t/h$^{-1}$ |

Insurance and taxation is 1.5% of TCI [37]. The cost of electricity includes power consumed by the pyrolysis and the biomass pretreatment plant. The power needed by the pyrolysis plant mainly for gas compression is estimated by Ringer [37] to be around 68 kWh/dry t of biomass. As far as the pretreatment facility is concerned, a typical rotary drum dryer used for reducing the level of biomass moisture consumes 32 kWh dry $t^{-1}$ [103]. Moreover, in order to reduce woodchips and miscanthus bales to a size of about 2–3 mm, 61 and 15 kWh dry $t^{-1}$ are consumed accordingly (Ringer [37] and Mani [104]). As a reference, another value often assumed for the power requirement of grinding is 50 kWh/ton of biomass [17]. It is estimated that grinding costs about 8.4 €/t of biomass fuel [105]. Twenty percent additional power consumption is considered in order to cover miscellaneous loads (electronic devices, lighting, etc.). A total of 193 and 138 kWh/dry t are therefore consumed in the case of woodchips and miscanthus respectively. These values are in general agreement with the Peacock report [42], where the electricity consumed by the Wellman and BTG fast pyrolysis processes is estimated equal to 236.6 and 158.5 kW respectively for a feed capacity of 2 dry t/h. According to the New Hampshire study [70], the electricity consumption of the fast pyrolysis unit ranges from 107 to 132 kWh/dry t for feed capacities from 100 to 400 dry t/day. The Ringer [37] study estimates the value at 175 kWh/dry t (550 dry t/day feedstock). The price of electricity is assumed equal 0.08 € $kWh^{-1}$ [62]. In the case of steam generation, any surplus electricity by the plant is sold to the grid.

The most important constituent of the pyrolysis plant's operating cost is the biomass purchase cost. It depends on the capacity of the unit as well as the price of biomass. The latter is made up of two parts. The primary component is called crop cost and reflects expenditures that include land preparation and cultivation (land ownership and exploitation related costs, utilities such as fertilizers and other chemicals, sowing equipment purchase or rental). Additional costs that concern the handling of biomass include its harvesting (labor and equipment), primary transformation (i.e. chipping or baling), field (local) and road (long distance) transport and storage [106]. The overall cost of biomass handling is highly connected to the properties of the species being examined (moisture, density, yield and annual availability), its source as well as to the local market status and economy trends. The price of biomass is additionally related to the characteristics of the supply chain selected. These include time scheduling, mass losses, power

and fuel requirements during each step of biomass handling and the modes of field harvesting (i.e. equipment and machinery), collection and storage (local vs. central) applied. Various purchase prices are reported in the literature, which range between 30 and 90 €/dry t. In the present work, the price of SRC woodchips and miscanthus is taken from [6]. It should be noted that the components of biomass purchase cost are taken independent of the utilization scheme considered. Consequently, the cost of biomass field storage (at about 15 €/t [107]), for instance, is the same for both scenarios (direct transport and bio-oil production) examined. The road transport cost component of biomass price is estimated separately, with the methodology described in Section 3. For the both fuels (SRC willow and miscanthus, a value of 10 dry t/ha of surface density is considered for the base case. This assumption is made taking into consideration a range of values reported from the literature for the harvest yield of SRC [108–111] and miscanthus [112–115].

The project life is assumed 25 years and the interest rate 7%. The annual capacity of the unit is 90% (7884 h of operation/year). These values are commonly assumed in various other relevant techno-economic assessments [6,17,66,70,116]. The fast pyrolysis process heat loads required, the percentage of remaining char for SRC willow and miscanthus as well the electricity produced by its combustion are estimated through the implementation of the AspenPlus™ [92] model and are given in Table 11 and Table 12.

**Table 11**
Fast pyrolysis process heat requirements.

| | |
|---|---|
| Biomass drying | Drying of biomass from initial moisture to 7% w/w |
| Pyrolysis reaction | Antal correlation **[117]** |
| Fluidizing gas reheat | Heating of recycle permanent gases stream from 50 °C (exiting the quencher) to 500 °C. Recycle gas stream fraction estimated with the assumption that the total fluidizing gas reheat requirement is equal to about 600 kWh/dry t of biomass **[6]** |

**Table 12**
Percentage of char available for electricity production, electricity produced from SPGU and electricity to grid (kWh/dry t of biomass feed to the plant) required for covering power loads.

| Biomass type | % of remaining char | Electricity produced | Electricity to grid |
|---|---|---|---|
| SRC willow | 65% | 218 kWh | 25 kWh |
| Miscanthus | 67% | 234 kWh | 96 kWh |

### 5.6. Bio-oil production cost – results and discussion

The bio-oil production cost for the base case scenario assumptions and its various components for capacities ranging from 1 to 80 dry t/h are plotted for woodchips in Fig. 10. It can be seen that the most significant cost component of bio-oil production is the cost of biomass purchase, which is roughly equal to 50% of the total cost. The cost of electricity required for the operation of the unit, as well as the capital investment cost has also a substantial impact.

The specific maintenance, insurance and taxation cost as well as the labor and capital costs tend to decrease for larger unit scales and are minimized in the case of an 80 dry t/h unit. It should be additionally noted that the cost of biomass collection, which is the cost of local transportation of the harvested biomass to the pyrolysis plant is insignificant compared to the other costs. Consequently, the impact of biomass surface density, which is directly connected to the cost of biomass collection, is negligible compared to that of other operation parameters. In the case of char utilization for electricity production, there is a slight increase in the capital investment. On the other hand, the income from selling surplus electricity results in an overall reduced production cost of bio-oil.

The variation of the cost of bio-oil production, excluding biomass purchase, for different values of labor (Germany and Spain), surface density $\delta$ and bio-oil yield is given in Table 13.

## 6. Scenario comparison-results and discussion

Having estimated all the cost components required, the two scenarios of direct biomass transportation and fast pyrolysis/bio-oil transportation are examined according to the principles presented in Section 2 and depicted in Fig. 11. By comparing the costs of the two scenarios, it is possible to decide which is more beneficial, given a circular surface of specified biomass surface density $\delta$.

In Fig. 12, the total specific cost as well as its primary components between the two scenarios examined (direct biomass transportation and fast pyrolysis-bio-oil transportation) are depicted. The cost is expressed per $kWh_{th}$ delivered at the yard of the central gasification unit C for various values of $D$. The fuel

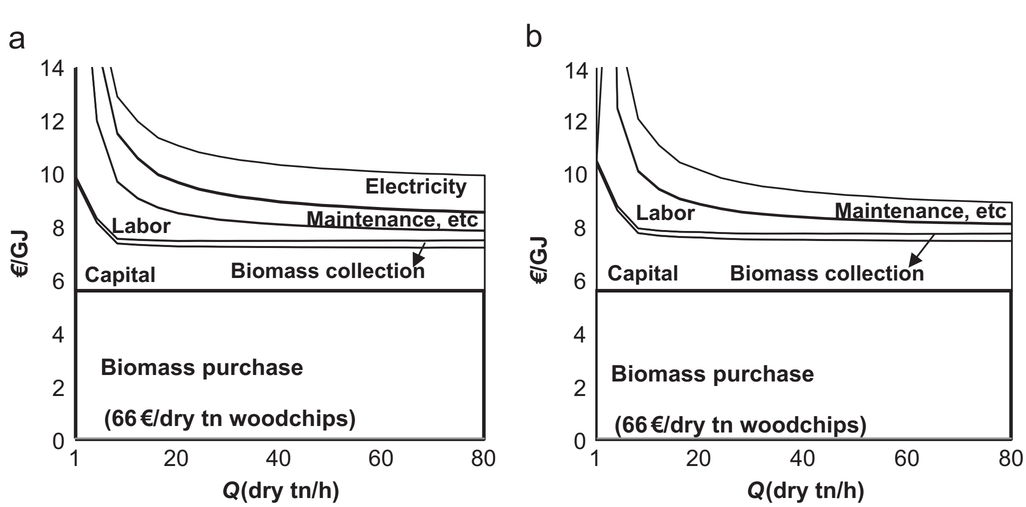



**Fig. 10.** Bio-oil production cost (€/GJ) for woodchips and miscanthus for varying values of pyrolysis plant capacity Q and biomass surface density (a) no steam generation (b) steam generation. The savings from the installation of SPGU and CT are also depicted for 20 dry t/h and 80 dry t/h units.

**Table 13**
Bio-oil production cost variation for various values of biomass surface density, labor cost and bio-oil yield for woodchips.

| | | |
|---|---|---|
| **Effect of biomass surface density, δ** | | |
| *Germany labor cost, bio-oil yield 65%* | **0.5 dry t/ha** | **20 dry t/ha** |
| $Q$= 5 dry t/ha | 14.66 €/GJ | 14.52 €/GJ |
| $Q$=20 dry t/ha | 10.71 €/GJ | 10.43€/GJ |
| $Q$=80 dry t/ha | 9.52 €/GJ | 9.04 €/GJ |
| **Effect of labor cost** | | |
| *δ=10 dry t/ha, bio-oil yield 65%* | **Spain** | **Germany** |
| $Q$= 5 dry t/ha | 13.39 €/GJ | 16.25 €/GJ |
| $Q$=20 dry t/ha | 9.85 €/GJ | 10.45 €/GJ |
| $Q$=80 dry t/ha | 8.79 €/GJ | 8.94 €/GJ |
| **Effect of bio-oil yield** | | |
| *Germany labor cost, δ=10 dry t/ha* | **60%** | **75%** |
| $Q$= 5 dry t/ha | 17.19 €/GJ | 13.76 €/GJ |
| $Q$=20 dry t/ha | 12.37 €/GJ | 9.90 €/GJ |
| $Q$=80 dry t/ha | 10.75 €/GJ | 8.60 €/GJ |

cost for the scenario involving intermediate conversion of the biomass to bio-oil is higher than the respective cost of direct biomass transportation for a central transportation distance (P–C) ranging from 100 to 500 km. As expected, the difference between the costs of the two scenarios tends to decrease for higher values of *D*, since the cost rate of bio-oil transportation is lower than the respective cost of biomass, as can be seen by the difference in the slope of the curves of the central transportation cost. However, the savings from the transportation advantages of bio-oil are insignificant. It should be noted that the biomass-to-bio-oil supply chain is more advantageous in the case of miscanthus. This is due to the fact that its transportation cost is much higher relatively to bio-oil than in the case of woodchips. Additionally, its conversion to bio-oil has a higher efficiency (higher yield and *HHV* of miscanthus-derived bio-oil) for the case examined. Assuming that the central unit located in C is an IGCC plant with an electrical efficiency equal to 40% for both biomass and bio-oil, the fuel costs for the plant per $kWh_e$ are estimated. For a variation of *D* from 100 to 500 km, these costs range from 0.04 to 0.06 €/$kWh_e$ (woodchips) and from 0.09 to 0.10 €/$kWh_{el}$ (woodchips derived bio-oil). For miscanthus the corresponding cost ranges are 0.04–0.07 €/kWhel (biomass) and 0.07–0.08 €/$kWh_e$ (bio-oil). As a showcase, the yard fuel cost is also estimated assuming that a methanol production bio-refinery is located in C. The mass ratio of methanol production per t of fuel input to the plant is estimated by the use of Aspen Plus ™ [92] software, assuming ideal conversion of the CO present in the syngas produced from the gasification of each biomass and bio-oil species. The gasification process model is carried out by oxygen at 800 °C and at a pressure of 30 bar, considering heat losses equal to 3% of the fuel input. The results are summarized in Table 14. It follows that the fuel cost for a methanol bio-refinery plant of woodchips and woodchips-derived bio-oil feedstock ranges from 335 to 522 €/t of methanol (biomass scenario) and from 528 to 626 €/t (bio-oil scenario) for an *D* distance ranging from 100 to 500 km. For miscanthus, the ranges of these values are 294–543 €/t (biomass) and 467–568 €/t (bio-oil), respectively. As of March 2013, the methanol price in Europe is 390 €/t [118]. It follows that the perspective for bio-methanol production at a competitive cost is thus restrained and further consideration should be made.

## 7. Conclusions

The bio-oil production through fast pyrolysis has been extensively investigated by academic and industrial organizations.

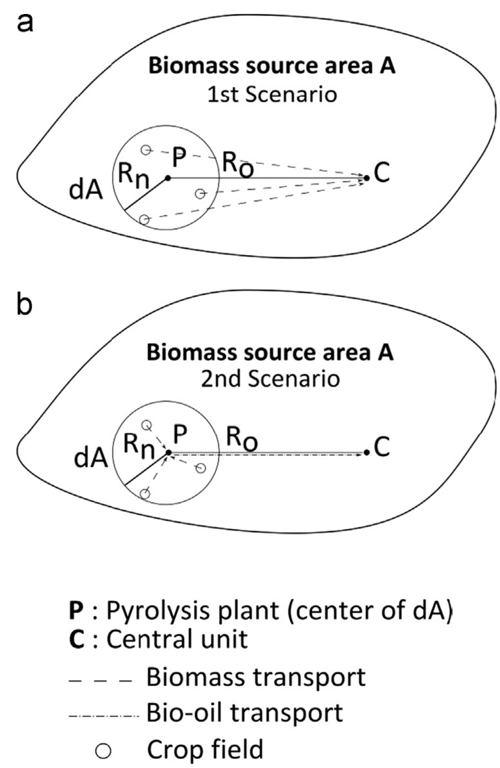



**Fig. 11.** Alternative transportation scenarios examined (a) Direct biomass transportation from circular surface to central plant C (b) Biomass conversion to bio-oil in pyrolysis plant situated in the center P of the circular surface and transportation of bio-oil to central plant C.

The main advantages of liquid fuels generally include the more efficient, cost-effective handling and storage, improved fuel properties and higher energy density in contrast to the solid fuels. Furthermore, bio-oil can be upgraded or utilized in various processing pathways and possible applications (i.e. power and heat generation, transportation fuels, chemicals and materials). The above features have led to an increasing interest for the commercialization of the fast pyrolysis technology, with many different reactor types and configurations being proposed internationally. Although no reactor design has been as far proven as definitively optimal, the general process principles for maximizing the yield of fast pyrolysis bio-oil have been determined.

In this study, the prospective of bio-oil as an alternative, cost competitive energy carrier from decentralized biomass sources to central biorefineries/gasification plants was investigated. The purpose of the analysis was to evaluate the potential of the increased energy density liquid fuel to reduce the higher costs inherent in the transportation of low energy density, solid biomass. The production cost of bio-oil was estimated by developing a methodology based on literature data and similar techno-economic studies of fast pyrolysis plants. It was determined that the purchase price of biomass has a definitive impact on the cost of bio-oil, since its contribution can be as much or even exceed the half of its value (at 66 €/dry t biomass price). As a result, bio-oil production schemes can be more economically attractive when sources of low cost biomass are accessible. The electricity consumption of fast pyrolysis units also constitutes a significant operating cost component, which can be alleviated by combusting the char and permanent gases for power production. It was also shown that significant economies of scale benefits emerge for pyrolysis plants of capacities larger than 20 dry t/h of biomass.

Moreover, a detailed model for calculating the transportation costs of solid biomass and bio-oil by trucks was formulated, integrating cost component data and transport-related legislative

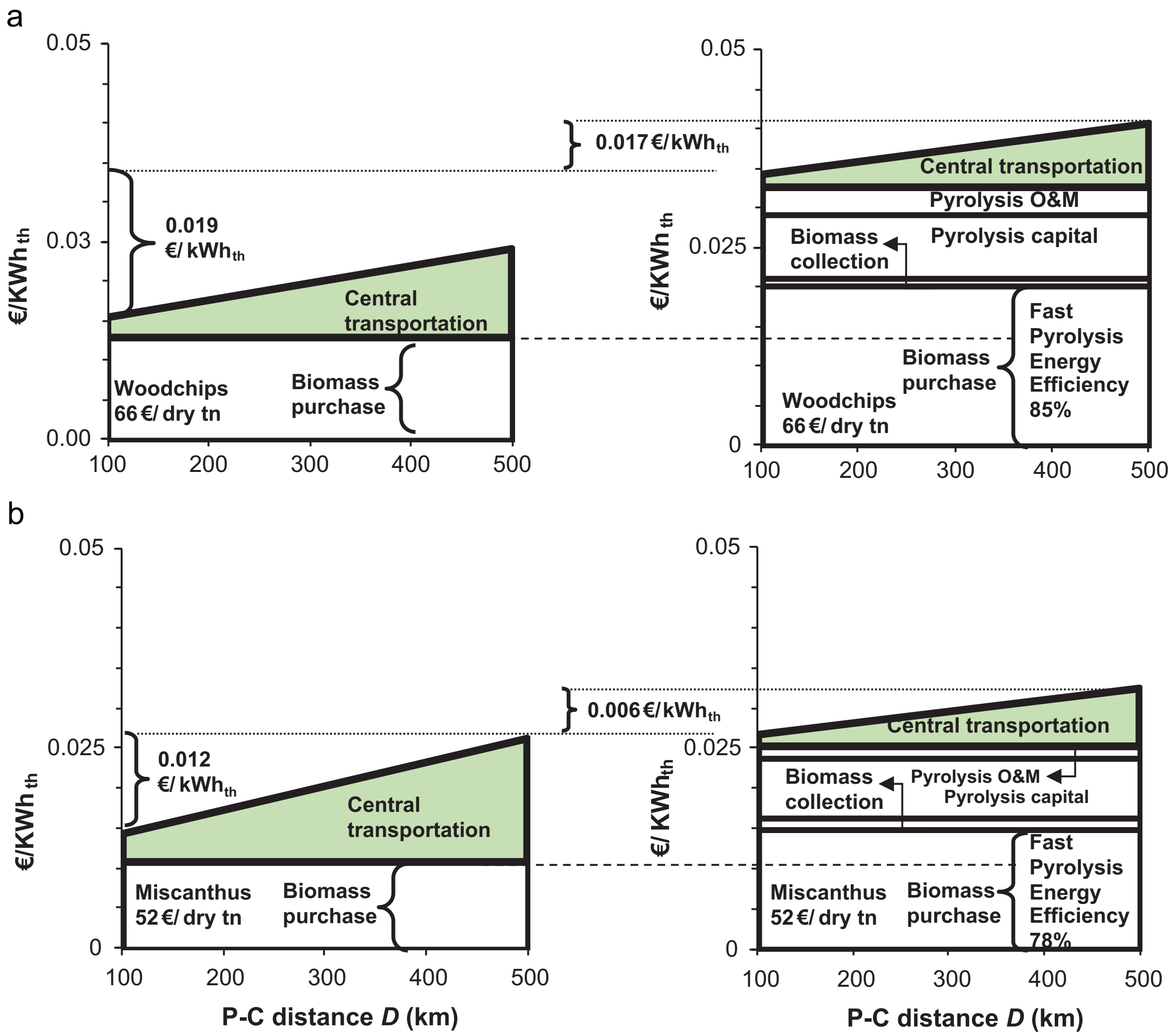



**Fig. 12.** Specific gasification plant yard fuel cost comparison between the two scenarios examined for (1) woodchips and (2) miscanthus, assuming a central transportation distance (between P and C) ranging from 100 to 500 km (a) Direct biomass transport to C (b) Intermediate fast pyrolysis in P and bio-oil transportation by pipeline to C. Biomass capacity $Q=80$ dry t/h, $\delta=10$ dry t/ha.

**Table 14**
Methanol conversion ratio for fuels examined.

| Fuel | % (w/w) methanol production ratio (gasification @ 800 °C 30 bar) |
|---|---|
| Woodchips (30% w/w moisture) | 21.1% |
| Bio-oil (woodchips derived) | 27.8% |
| Miscanthus (15% w/w moisture) | 16.5% |
| Bio-oil (miscanthus derived) | 26.9% |

regulations and technical specifications. Although bio-oil exhibits a lower specific transportation (0.81vs 1.08 €/GJ for woodchips, vs 1.60 €/GJ for miscanthus at 100 km) than solid biomass, a major obstacle for fully taking advantage of its high energy density is posed by technical and legislative restrictions on the maximum gross vehicle weight of trucks. For this reason, the transportation of bio-oil via pipeline becomes more cost-efficient for higher capacities (over 15 t/h).

A scenario involving intermediate conversion of biomass to bio-oil through the fast pyrolysis process and bio-oil transportation to a central bio-refinery unit was compared to a scenario of direct biomass transportation to the same unit. A semi-empirical model was employed to estimate the yields and energy content of the pyrolysis products as well as the energy balance of the process. Under the most favorable (from an economic standpoint) conditions assumed regarding the fast pyrolysis scenario (involving an 80 dry t/h unit, steam and electricity production and pipeline transportation), it is concluded that the reduction of the transportation costs (owed to the liquid phase of bio-oil) cannot make up for the increased capital and operation costs related to the fast pyrolysis process for a range of distances between 100 and 500 km. For woodchips, the fuel yard cost of the direct biomass transport scenario is by 0.019 and 0.017 €/$kWh_{th}$ lower than the scenario including conversion to bio-oil for transportation distances of 100 and 500 km respectively. The equivalent values in the case of miscanthus are 0.012 and 0.006 €/$kWh_{th}$. These results indicate that the relative decrease in the transportation costs through the conversion of biomass to bio-oil can be especially beneficial in the case of lower energy density biomass species, even when considering a lower energy efficiency of the process (as is the case in the present work).

Conclusively, given the assumptions and the results of the present study, it seems that for the time being fast pyrolysis has the potential of fuel transport cost reduction mainly for large scale, low energy density biomass production schemes and for very long transport distances, suggesting utilization schemes on a multinational level. However, improvements in the conversion efficiency along with a reduction of the capital-related charges of the technology have the potential of making bio-oil more cost competitive as an energy carrier for even smaller distances.

It should be, finally, also stressed that in order to have a more complete evaluation of bio-oil's potential role as a cost efficient energy carrier, the economic impact of the advantages of bio-oil over biomass regarding their use in a bio-refinery (concerning handling, storage, pretreatment, syngas quality) needs to be additionally assessed.

## References

[1] Van de Velden M, Baeyens J, Brems A, Janssens B, Dewil R. Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction. Renew Energy 2010;35:232–42.
[2] Badger PC, Fransham P. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs—a preliminary assessment. Biomass Bioenergy 2006;30:321–5.
[3] Francescato V., Antonini E., Bergomi L. Wood fuels handbook, production, quality requirements, Trading: AIEL-Italian Energy Association; 2008.
[4] Polagye BL, Hodgson KT, Malte PC. An economic analysis of bio-energy options using thinnings from overstocked forests. Biomass Bioenergy 2007;31:105–25.
[5] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. Biomass Bioenergy 2012;38:68–94.
[6] Rogers JG, Brammer JG. Estimation of the production cost of fast pyrolysis bio-oil. Biomass Bioenergy 2012;36:208–17.
[7] Garcia-Perez M, Shen J, Wang XS, Li C-Z. Production and fuel properties of fast pyrolysis oil/bio-diesel blends. Fuel Process Technol 2010;91:296–305.
[8] Kudakasseril Kurian J, Raveendran Nair G, Hussain A, Feedstocks Vijaya Raghavan GS. logistics and pre-treatment processes for sustainable lignocellulosic biorefineries: a comprehensive review. Renew Sustain Energy Rev 2013;25:205–19.
[9] Pootakham T, Kumar A. Bio-oil transport by pipeline: a techno-economic assessment. Bioresour Technol 2010;101:7137–43.
[10] Kumar A, Cameron JB, Flynn PC. Pipeline transport and simultaneous saccharification of corn stover. Bioresour Technol. 2005;96:819–29.
[11] Kumar A., Cameron J., Flynn P. Large-scale ethanol fermentation through pipeline delivery of biomass. In: Davison B., Evans B., Finkelstein M., McMillan J., editors. Twenty-sixth symposium on biotechnology for fuels and chemicals: Humana Press; 2005. p. 47–58.
[12] Trippe F, Frohling M, Schultmann F, Stahl R, Henrich E. Techno-economic analysis of fast pyrolysis as a process step within biomass-to-liquid fuel production. Waste Biomass Valoriz 2010;1:415–30.
[13] Choi HS, Choi YS, Park HC. Fast pyrolysis characteristics of lignocellulosic biomass with varying reaction conditions. Renew Energy 2012;42:131–5.
[14] Ng KS, Sadhukhan J. Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power. Biomass Bioenergy 2011;35:1153–69.
[15] Butler E, Devlin G, Meier D, McDonnell K. A review of recent laboratory research and commercial developments in fast pyrolysis and upgrading. Renew Sustain Energy Rev 2011;15:4171–86.
[16] Sarkar S, Kumar A. Large-scale biohydrogen production from bio-oil. Bioresour Technol 2010;101:7350–61.
[17] Mark M, Wright JAS, Robert C, Brown. Techno-Economic. Analysis of biomass fast pyrolysis to transportation fuels. National Renewable Energy Laboratory; 2010.
[18] Doug E. IEA bioenergy task 34-pyrolysis. 2013.
[19] Czernik S, Bridgwater AV. Overview of applications of biomass fast pyrolysis oil. Energy Fuels 2004;18:590–8.
[20] Chiaramonti D, Oasmaa A, Solantausta Y. Power generation using fast pyrolysis liquids from biomass. Renew Sustain Energy Rev 2007;11:1056–86.
[21] K.W. Morris, W.L. Johnson, R. Thamburaj Fast pyrolysis of biomass for green power generation. First world conference on biomass for energy and industry. Sevilla, Spain; 2000.
[22] Ikura M, Stanciulescu M, Hogan E. Emulsification of pyrolysis derived bio-oil in diesel fuel. Biomass Bioenergy 2003;24:221–32.
[23] Mohan D, Pittman CU, Steele PH. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 2006;20:848–89.
[24] Bridgwater AV, Meier D, Radlein D. An overview of fast pyrolysis of biomass. Org Geochem 1999;30:1479–93.
[25] Nikolopoulos N, Isemin R, Atsonios K, Kourkoumpas D, Kuzmin S, Mikhalev A, et al. Modeling of wheat straw torrefaction as a preliminary tool for process design. Waste Biomass Valor 2013;4:409–20.
[26] Lu Q, Li W-Z, Zhu X-F. Overview of fuel properties of biomass fast pyrolysis oils. Energy Convers Manag 2009;50:1376–83.
[27] DeSisto WJ, Hill N, Beis SH, Mukkamala S, Joseph J, Baker C, et al. Fast pyrolysis of pine sawdust in a fluidized-bed reactor. Energy Fuels 2010;24: 2642–51.
[28] Akhtar J, Saidina Amin N. A review on operating parameters for optimum liquid oil yield in biomass pyrolysis. Renew Sustain Energy Rev 2012;16:5101–9.
[29] Neves D, Thunman H, Matos A, Tarelho L, Gómez-Barea A. Characterization and prediction of biomass pyrolysis products. Prog Energy Combust Sci 2011;37:611–30.
[30] Oasmaa A, Solantausta Y, Arpiainen V, Kuoppala E, Sipilä K. Fast pyrolysis bio-oils from wood and agricultural residues. Energy Fuels 2009;24:1380–8.
[31] Fahmi R, Bridgwater AV, Donnison I, Yates N, Jones JM. The effect of lignin and inorganic species in biomass on pyrolysis oil yields, quality and stability. Fuel 2008;87:1230–40.
[32] Nowakowski DJ, Woodbridge CR, Jones JM. Phosphorus catalysis in the pyrolysis behaviour of biomass. J Anal Appl Pyrolysis 2008;83:197–204.
[33] Nowakowski DJ, Jones JM, Brydson RMD, Ross AB. Potassium catalysis in the pyrolysis behaviour of short rotation willow coppice. Fuel 2007;86: 2389–402.
[34] Agblevor FA, Besler S. Inorganic compounds in biomass feedstocks. 1. effect on the quality of fast pyrolysis oils. Energy Fuels 1996;10:293–8.
[35] Lee K-H, Kang B-S, Park Y-K, Kim J-S. Influence of reaction temperature, pretreatment, and a char removal system on the production of bio-oil from rice straw by fast pyrolysis, using a fluidized bed. Energy Fuels 2005;19:2179–84.
[36] Milne Ta AF, Davis M, Deutch S, Johnson D. A review of chemical composition of fast pyrolysis oils. In: Bridgwater AV, editor. Developments in thermochemical biomass conversion. London: Blackie Academic & Professional; 1997. p. 409–24.
[37] Ringer M, Putsche V, Scahill J. Large scale pyrolysis: a technology assessment and economic analysis. National Renewable Energy Laboratory; 2006.
[38] Meier D, van de Beld B, Bridgwater AV, Elliott DC, Oasmaa A, Preto F. State-of-the-art of fast pyrolysis in IEA bioenergy member countries. Renew Sustain Energy Rev 2013;20:619–41.
[39] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renew Sustain Energy Rev 2002;6:181–246.
[40] Lehto J, Oasmaa A, Solantausta Y, Kyto M, Chiaramonti D. Review of fuel oil quality and combustion of fast pyrolysis bio-oils from lignocellulosic biomass. Appl Energy 2014;116:178–90.
[41] Dinjus E, Dahmen N, Koerber R. Synthetic fuel from biomass – the bioliq process. Shanghai, China: IFAT; 2008.
[42] Peacocke G, Bridgwater A, Brammer J. Techno-economic assessment of power production production from the Wellman and BTG fast pyrolysis processes. In: Bridgwater A, Boocock D, editors. Science in thermal and chemical biomass conversion; 2006. p. 1785.
[43] Brammer JG, Lauer M, Bridgwater AV. Opportunities for biomass-derived “bio-oil” in European heat and power markets. Energy Policy 2006;34: 2871–80.
[44] Bradley D. European market study for BioOil (pyrolysis oil). Ottawa, Ontario, Canada: Climate Change Solutions; 2006.
[45] Bryan P. Biomass program overview. Washington, D.C.: Biomass Program Peer Review; 2011.
[46] Karampinis E., Grammelis P., Kakaras E. Current status and future of co-firing in five EU Countries (BE, GR, HU, IT, PO): effect of support schemes, sustainability criteria and biomass markets. In: Nineteenth European biomass conference. Berlin, Germany; 2011. p. 2517–22.
[47] Karkania V, Fanara E, Zabaniotou A. Review of sustainable biomass pellets production – a study for agricultural residues pellets' market in Greece. Renew Sustain Energy Rev 2012;16:1426–36.
[48] Boukis I, Vassilakos N, Kontopoulos G, Karellas S. Policy plan for the use of biomass and biofuels in Greece: Part II: logistics and economic investigation. Renew Sustain Energy Rev 2009;13:703–20.
[49] Skoulou V, Mariolis N, Zanakis G, Zabaniotou A. Sustainable management of energy crops for integrated biofuels and green energy production in Greece. Renew Sustain Energy Rev 2011;15:1928–36.
[50] Zabaniotou AA, Karabelas AJ. The Evritania (Greece) demonstration plant of biomass pyrolysis. Biomass Bioenergy 1999;16:431–45.
[51] Marimon N.P. Integrated sustainability analysis of innovative uses of forest biomass. Bio-oil as an energy vector [Doctoral]. Universitat Autonoma de Barcelona (UAB) 2010.
[52] Searcy E, Flynn P, Ghafoori E, Kumar A. The relative cost of biomass energy transport. Appl Biochem Biotechnol 2007;136–140:639–52.
[53] Rogers JG, Brammer JG. Analysis of transport costs for energy crops for use in biomass pyrolysis plant networks. Biomass Bioenergy 2009;33:1367–75.
[54] Bridgwater AV. Renewable fuels and chemicals by thermal processing of biomass. Chem Eng J 2003;91:87–102.
[55] Transport UDf. Truck specification for best operational efficiency. UK Department for Transport; 2010.
[56] Huisman W, Venturi P, Molenaar J. Costs of supply chains of Miscanthus giganteus. Ind Crops Prod 1997;6:353–66.
[57] Rentizelas AA, Tolis AJ, Tatsiopoulos IP. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew Sustain Energy Rev 2009;13:887–94.

[58] Badger PC. Processing cost analysis for biomass feedstocks. Oak Ridge, Tennessee: Oak Ridge National Laboratory; 2002.
[59] Chariton valley biomass project: draft fuel supply plan. Antares Group Incorporated; 2002.
[60] Dynamotive. 〈http://dynamotive.com〉.
[61] Devlin G., Talbot B. Deriving cooperative biomass resource transport supply strategies in meeting co-firing energy regulations: a case for peat and wood fibre in Ireland. Appl Energy. 2014;113:1700–9.
[62] Europe's energy portal. 〈http://www.energy.eu〉.
[63] Mobility and transport - road safety.〈http://ec.europa.eu/transport/road_safety/specialist/knowledge/speed/speed_limits/current_speed_limit_policies.htm〉.
[64] Ruiz JA, Juárez MC, Morales MP, Muñoz P, Mendívil MA. Biomass logistics: financial and environmental costs. Case study: 2 MW electrical power plants. Biomass Bioenergy 2013;56:260–7.
[65] Craig Rawlings B.R., Chuck Seeley. A. Study of how to decrease the costs of collecting, processing and transporting slash. US Forest Service; 2004.
[66] Wright MM, Daugaard DE, Satrio JA, Brown RC. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 2010;89(1):S2–10.
[67] Gregoire C.E. Technoeconomic analysis of the production of biocrude from wood National Renewable Energy Laboratory; 1992.
[68] Gregoire CE, Bain RL. Technoeconomic analysis of the production of biocrude from wood. Biomass Bioenergy 1994;7:275–83.
[69] Cottam ML, Bridgwater AV. Techno-economic modelling of biomass flash pyrolysis and upgrading systems. Biomass Bioenergy 1994;7:267–73.
[70] al HMe. Technical, environmental and economic feasibility of bio-oil in New Hamphshire's North Country. New Hampshire, England, UK: New Hampshire Industrial Research Center; 2002.
[71] Arthur J. Power and Associates I. Feasibility study: one thousand tons per day feedstock wood to crude pyrolysis oils plant 542,000 pounds per year using fast pyrolysis of biomass process. Golden, CO; 1991.
[72] Sorenson CB. A comparative financial analysis of fast pyrolysis plants in Southwest Oregon. Missoula, MT: The University of Montana; 2001.
[73] Islam MN, Ani FN. Techno-economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel. Bioresour Technol 2000;73:67–75.
[74] Czernik S, French R. Distributed production of hydrogen by auto-thermal reforming of fast pyrolysis bio-oil. Int J Hydrogen Energy 2014;39:744–50.
[75] Soantausta Y. Work Package 5: techno-economic assessment, the Finnish case study. VTT Technical Research Centre of Finland; 2003.
[76] Jones S., J.E., Holladay, C., Valkenburg D., Stevens C., Walton C., Kinchin, et al. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. Pacific Northwest National Laboratory; 2009.
[77] Brown TR, Thilakaratne R, Brown RC, Hu G. Regional differences in the economic feasibility of advanced biorefineries: fast pyrolysis and hydroprocessing. Energy Policy 2013;57:234–43.
[78] Shen J, Wang X-S, Garcia-Perez M, Mourant D, Rhodes MJ, Li C-Z. Effects of particle size on the fast pyrolysis of oil mallee woody biomass. Fuel 2009;88:1810–7.
[79] Bridgwater AV. Principles and practice of biomass fast pyrolysis processes for liquids. J Anal Appl Pyrolysis. 1999;51:3–22.
[80] Bridgwater AV. Peacocke GVC. Fast pyrolysis processes for biomass. Renew Sustain Energy Rev 2000;4:1–73.
[81] Svoboda K, Pohořelý M, Hartman M, Martinec J. Pretreatment and feeding of biomass for pressurized entrained flow gasification. Fuel Process Technol 2009;90:629–35.
[82] C.R. Shaddix DRH. Combustion properties of biomass flash pyrolysis oils: final project report. Sandia National Laboratories; 1999.
[83] Diebold JP. A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis Bio-Oils. National Renewable Energy Laboratory; 2000.
[84] Boukis IP, Grammelis P, Bezergianni S, Bridgwater AV. CFB air-blown flash pyrolysis. Part I: engineering design and cold model performance. Fuel 2007;86:1372–86.
[85] He F, Yi W, Bai X. Investigation on caloric requirement of biomass pyrolysis using TG–DSC analyzer. Energy Convers Manag 2006;47:2461–9.
[86] White JE, Catallo WJ, Legendre BL. Biomass pyrolysis kinetics: a comparative critical review with relevant agricultural residue case studies. J Anal Appl Pyrolysis 2011;91:1–33.
[87] Heo HS, Park HJ, Yim J-H, Sohn JM, Park J, Kim S-S, et al. Influence of operation variables on fast pyrolysis of Miscanthus sinensis var. purpurascens. Bioresour Technol 2010;101:3672–7.
[88] Mullen CA, Boateng AA, Goldberg NM, Lima IM, Laird DA, Hicks KB. Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass Bioenergy 2010;34:67–74.
[89] Kim KH, Kim T-S, Lee S-M, Choi D, Yeo H, Choi I-G, et al. Comparison of physicochemical features of biooils and biochars produced from various woody biomasses by fast pyrolysis. Renew Energy 2013;50:188–95.
[90] Channiwala SA, Parikh PP. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 2002;81:1051–63.
[91] Friedl A, Padouvas E, Rotter H, Varmuza K. Prediction of heating values of biomass fuel from elemental composition. Anal Chim Acta 2005;544:191–8.
[92] AspenTech. Aspen Plus.
[93] Peters M, Timmerhaus K. Plant design and economics for chemical engineers. 4th ed.. New York: McGraw-Hill; 1991.
[94] J. Richard Hess KKao Feasibility of a producer owned ground-straw feedstock supply system for bioethanol and other products. Idaho National Laboratory; 2006.
[95] Phillips S, Jechura AA, J, Dayton D. Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. National Renewable Energy Laboratory; 2007.
[96] Spath P, Eggeman AA, T, Ringer M, Wallace B, Jechura J. Biomass to hydrogen production detailed design and economics utilizing the Battelle Columbus Laboratory indirectly-heated gasifier. National Renewable Energy Laboratory; 2005.
[97] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenergy 2005;29:114–34.
[98] Goto K, Yogo K, Higashii T. A review of efficiency penalty in a coal-fired power plant with post-combustion $CO_2$ capture. Appl Energy 2013;111:710–20.
[99] Yeh S, Rubin ES. A centurial history of technological change and learning curves for pulverized coal-fired utility boilers. Energy 2007;32:1996–2005.
[100] Atsonios K., Violidakis I., Agraniotis M., Grammelis P., Nikolopoulos N., Kakaras E. Thermodynamic analysis and comparison of retrofitting pre-drying concepts at existing lignite power plants. Appl Thermal Eng, http://dx.doi.org/10.1016/j.applthermaleng.2013.11.007.
[101] Perry P, Green D. Perry's chemical engineer's handbook. 7th ed.. New York: McGraw-Hill; 1999.
[102] 〈http://epp.eurostat.ec.europa.eu/portal/page/portal/labour_market/earnings/main_tables〉.
[103] Brammer JG, Bridgwater AV. Drying technologies for an integrated gasification bio-energy plant. Renew Sustain Energy Rev 1999;3:243–89.
[104] Mani S, Tabil LG, Sokhansanj S. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass Bioenergy 2004;27:339–52.
[105] Sokhansanj S, Kumar A, Turhollow AF. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenergy 2006;30:838–47.
[106] University SL, Technology TUo, CERTH, IVALSA, Agency TE. The Bioenergy System Planners Handbook-BISYPLAN web-based handbook. 2012.
[107] Caslin B., Finnan J., Easson L. Miscanthus Best Practice Guidelines: Agri-Food and Biosciences Institute; 2011.
[108] DEFRA. Best Practice Guidelines For Applicants to Defra's Energy Crops Scheme. In: Affairs DfEFaR, editor. Admail 6000, London SW1a 2XX: Defra Publications; 2004. p. 6.
[109] Barry Caslin Dr John Finnan, McCracken DA. Short rotation coppice willow best practice guide. In: Development DoAaR. Ireland: Ecclesville printing services; 2010.
[110] Wolbert-Haverkamp M, Musshoff O. Are short rotation coppices an economically interesting form of land use? A real options analysis Land Use Policy 2014;38:163–74.
[111] Faasch RJ, Patenaude G. The economics of short rotation coppice in Germany. Biomass Bioenergy 2012;45:27–40.
[112] Kristensen E.F. Harvesting and handling of miscanthus, Danish experiences. Danish Institute of Agricultural Sciences, Research Centre Bygholm. p. 3–4.
[113] McKendry P. Energy production from biomass (part 1): overview of biomass. Bioresour Technol 2002;83:37–46.
[114] Elbersen W. Switchgrass and Miscanthus as energy crops-agricultural aspects. energy crops & biogas, pathways to success? The Netherlands: Wageningen University; 2005.
[115] Vyn RJ, Virani T, Deen B. Examining the economic feasibility of miscanthus in Ontario: an application to the greenhouse industry. Energy Policy 2012;50: 669–76.
[116] Trippe F, Frohling M, Schultmann F, Stahl R, Henrich E. Techno-economic assessment of gasification as a process step within biomass-to-liquid (BtL) fuel and chemicals production. Fuel Process Technol 2011;92:2169–84.
[117] Reed T., Cowdery C. Heat flux requirements for fast pyrolysis and a new method for generating biomass vapor. Production of primary pyrolysis oils – fundamentals. Denver 1987. p. 68–81.
[118] Methanex. 〈http://www.methanex.com/products/methanolprice.html〉. 2013.